$K_L \to \pi^+\pi^-e^+e^-$ Analysis Status before the DPF03 Meeting

Alexander Golossanov
University of Virginia

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KTeV Collaboration Meeting

Fermilab†

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†In this document (if you have access to the internet) you can click on any text in *purple color* for additional information

1. Talk Outline

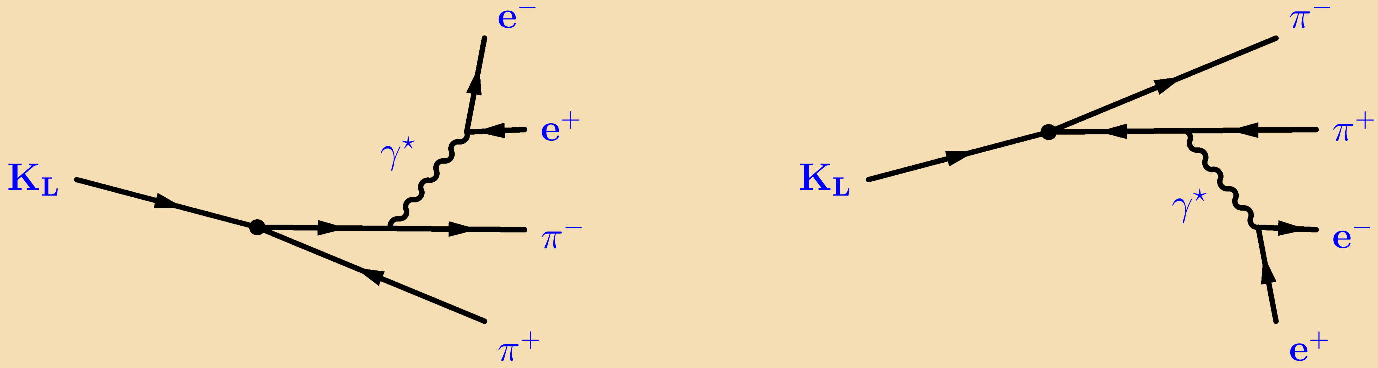
√ Complete **set of results has been obtained**.

√ Studies of **Systematic Uncertainties** are under way.

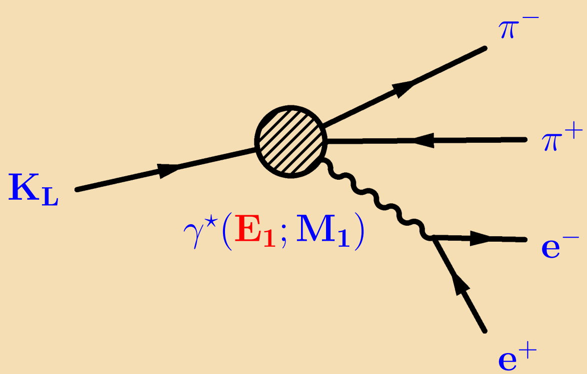
√ **New big systematics** was discovered and the uncertainty has been estimated. The sources of this effect are **under investigation**.

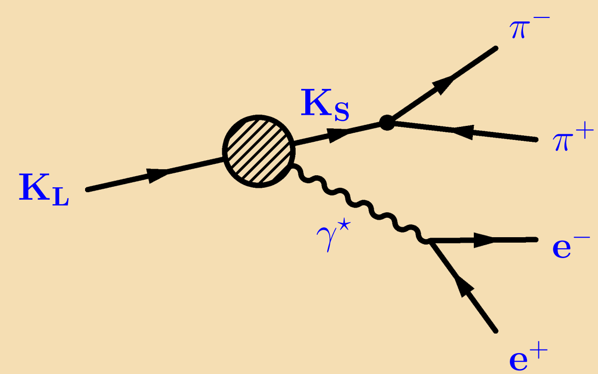
√ Discussion about **what exactly can be shown at DPF**.

2. Contributions to the Decay $K_L \to \pi^+\pi^-e^+e^-$



Inner Bremsstrahlung (IB) — *Indirect $\not{C}P$*





Direct Emission (DE)

E_1 — ***Indirect $\not{C}P$***

M_1 — ***CP Conserving***

K^0 Charge Radius (CR)

CP Conserving

3. Expressions for the Form Factors

√ **Inner Bremsstrahlung**: $\mathbf{g_{IB}} = |\eta_{+-}| e^{i(\delta_0(M_K) + \Phi_{+-})}$

√ M_1 **Direct Emission**: $\mathbf{g_{M_1}} = i e^{i\delta_1(M_{\pi\pi})} \times \mathbf{F}\left(\frac{a_1}{a_2}; \tilde{g}_{M_1}\right)$,

where

$$\mathbf{F} = \tilde{\mathbf{g}}_{\mathbf{M_1}} \left[1 + \frac{\mathbf{a1/a2}}{(M_\rho^2 - M_K^2) + 2M_K E_{ee}} \right]$$

√ E_1 **Direct Emission**: $\mathbf{g_{E_1}} = \frac{|\mathbf{g_{E_1}}|}{|\mathbf{g_{M_1}}|} e^{i(\delta_1(M_{\pi\pi}) + \Phi_{+-})} \times \mathbf{F}\left(\frac{a_1}{a_2}; \tilde{g}_{M_1}\right)$

√ **Charge Radius**: $\mathbf{g_{CR}} = |\mathbf{g_{CR}}| e^{i\delta_0(M_{\pi\pi})}$,

where $|\mathbf{g_{CR}}| = -\frac{1}{3} \langle \mathbf{R^2(K^0)} \rangle M_K^2$

4. History of $K_L \to \pi^+\pi^-e^+e^-$ Measurements

When?	Measured Values					
	$\tilde{g}_{M_1}$	a_1/a_2, GeV^2/c^2	$\lvert g_{CR}\rvert$	$\lvert g_{E_1}\rvert$	$\mathcal{A}$, %	$\mathcal{BR}$, $\times 10^{-7}$
Before KTeV	$F = 0.76$		0.15	0.038	-	-
one day, *PRL(1996)*	-	-	-	-	-	$3.2 \pm .6$
Winter, ICHEP98	-	-	-	-	-	$3.32 \pm .14$
'97, EPS HEP99	-	-	-	-	-	$3.63 \pm .11$
'97, *PRL(2000)*	$1.35 \pm .20$	$-.72 \pm .03$	-	-	13.6 ± 2.5	-
'96, *PRL(2001)*	-	$-.734 \pm .034$	-	-	-	-
'97, BCP4(2001)	-	-	$.100 \pm .018$	-	-	-
'97+'99, DPF2002	$1.10 \pm .10$	$-.75 \pm .03$	-	-	13.3 ± 1.4	-
", ", Madison	$1.20 \pm .13$	$-.73 \pm .03$	$.19 \pm .01$	-	-	-
", ", Sept 2002	$1.15 \pm .12$	$-.73 \pm .02$	$.18 \pm .02$	$< .03$	-	-
", ", Jan 2003	$1.14 \pm .12$	$-.73 \pm .02$	$.20 \pm .01$	$.09 \pm .03$	14.1 ± 1.4	-
", ", today	$1.27 \pm .12$	$-.71 \pm .02$	$.25 \pm .01$	$.14 \pm .03$	13.9 ± 1.4	$3.67 \pm .07$

5. Fitting Procedure

√ **Data**: 5241 events from '97 and '99 runs.

√ The best **fitting model**

- New strong interaction **phase shifts**.
-

$$\log\mathcal{L}\left(\vec{\alpha}\right) = \left[\sum_{i=1}^{N_d} \log w_i\left(\vec{\alpha}, \vec{x}\right)\right] - N_d \log \sum_{j=1}^{N_{mc}} \frac{w_i(\vec{\alpha}, \vec{x})}{w_i(\vec{\alpha_0}, \vec{x})}$$

where $\vec{x}$ is the vector of measured variables and $\vec{\alpha}$ is the vector of parameters to be estimated, i.e.

$$\vec{\alpha} = \left(\frac{a_1}{a_2}; g_{M_1}; g_{CR}; g_{E1}\right); \qquad \vec{x} = (\phi, \theta_{e^+}, \theta_{\pi^-}, M_{\pi\pi}, M_{ee})$$

√ **"Big MC Sample(s)"** generated with a fixed set of parameters.

6. Changing the "Big MC Samples"

Each sample is $\approx$ 600,000 events.

√ **"newP" sample**:
Generation parameters: g_{M_1} **= 1.15,** $\frac{a_1}{a_2}$ **= -.73,** g_{CR} **= .18,** g_{E_1} **= .0003**

√ **"jan03"**:
Generation parameters: g_{M_1} **= 1.14,** $\frac{a_1}{a_2}$ **= -.73,** g_{CR} **= .20,** g_{E_1} **= .09**

√ **"mar03"**:
Generation parameters: g_{M_1} **= 1.26,** $\frac{a_1}{a_2}$ **= -.715,** g_{CR} **= .24,** g_{E_1} **= .144**

√ **"yhi"**:
Generation parameters: g_{M_1} **= 1.35,** $\frac{a_1}{a_2}$ **= -.70,** g_{CR} **= .26,** g_{E_1} **= .15**

7. Systematics Due to the Different "Big MC Sample"

Sample, # *size = 300,000×#*	Fit Results				Calculated	
	$\tilde{g}_{M_1}$	a_1/a_2, GeV^2/c^2	$\lvert g_{CR}\rvert$	$\frac{\lvert g_{E_1}\rvert}{\lvert g_{M_1}\rvert}$	$\mathcal{A}(\pm 1.4)$, %	$\mathcal{BR}(\pm .07)$, $\times 10^{-7}$
newP	1.157	−.732	.224	.100	14.1	-
jan03	1.258	−.715	.240	.144	13.8	3.68
mar03	1.353	−.702	.260	.150	13.7	3.67
yhi	1.329	−.704	.269	.173	-	-

√ Average and take the **maximum variation** to estimate the uncertainty (**it won't be smaller!**):

$$g_{M1} = 1.27 \pm 0.12(\text{stat}) \pm 0.19 \pm 0.06(\text{DPF02})$$

$$\frac{a_1}{a_2} = -0.71 \pm 0.03(\text{stat}) \pm 0.02 \pm 0.02(\text{DPF02})$$

$$g_{CR} = 0.25 \pm 0.01(\text{stat}) \pm 0.05 \pm \ldots$$

$$\frac{|g_{E1}|}{|g_{M1}|} = 0.14 \pm 0.03(\text{stat}) \pm 0.07 \pm \ldots$$

$$\mathcal{A} = (13.9 \pm 1.4(\text{stat}) \pm 0.04 \pm 0.01(\text{DPF02}))\,\%$$

$$\mathcal{BR} = (3.67 \pm 0.07(\text{stat}) \pm 0.01 \pm \ldots) \times 10^{-7}$$

√ Alternatively could use the latest fit result, assumming it converges to a certain value.

8. What Could be the Origin of the Problem?

√ **The fitter** has errors or bugs. — **perhaps!**

- **Minimization routine** — checked. Some variation could be in the third digit after the decimal point. So, **"not likely"**.
- **The Likelihood function** was constructed incorrectly? **Checked many times**, but mostly for the values of parameters close to the fit results. **Investigating** more distant points **shows similar variations**. So, **may be this is the reason?**.
- ...

√ **MC** simulation does not describe our data well enough? — **unlikely**

- **Background** is present in MC, but not in the data. — **unlikely, because it's small**
- **Error or bug** in the simulation or analysis code? — **always possible, but hard to tell**
- Unsatisfactory **simulation of the detector** (v5_06 vs v6_01)? — **may be not**
- **Theoretical model** is not adequate? **shouldn't matter**
- ...

√ **Any other** potential problems?..

9. Fit "Fake Data" to Check the Likelihood Function

√ **One** "fake data sample" (g_{M_1}= **0.5**, $\frac{a_1}{a_2}$= -0.73, g_{E_1}= 0.0003, g_{CR}= 0.18)

Sample, #	Fit Results				Calculated	
size = 300,000×#	$\tilde{\mathbf{g}}_{\mathbf{M_1}}$	$\mathbf{a_1/a_2}$, GeV^2/c^2	$\lvert\mathbf{g_{CR}}\rvert$	$\frac{\lvert\mathbf{g_{E_1}}\rvert}{\lvert\mathbf{g_{M_1}}\rvert}$	$\mathcal{A}$, %	$\mathcal{BR}$, $\times 10^{-7}$
newP	0.780	−.644	.169	.000	-	-
oldP	0.616	−.680	.166	.000	-	-
bfake	0.542	−.693	.163	.000	-	-
dpf02	0.600	−.687	.167	.000	-	-
jan03	0.673	−.658	.167	.028	-	-
mar03	0.650	−.662	.169	.039	-	-

√ **Another one**, generated with g_{M_1}= **2.0**, $\frac{a_1}{a_2}$= -0.73, g_{E_1}= 0.0003, g_{CR}= 0.18

Sample, #	Fit Results				Calculated	
size = 300,000×#	$\tilde{\mathbf{g}}_{\mathbf{M_1}}$	$\mathbf{a_1/a_2}$, GeV^2/c^2	$\lvert\mathbf{g_{CR}}\rvert$	$\frac{\lvert\mathbf{g_{E_1}}\rvert}{\lvert\mathbf{g_{M_1}}\rvert}$	$\mathcal{A}$, %	$\mathcal{BR}$, $\times 10^{-7}$
newP	1.954	−.716	.270	.048	-	-
oldP	2.012	−.730	.225	.000	-	-
bfake	1.901	−.721	.224	.000	-	-
dpf02	2.001	−.731	.223	.000	-	-
jan03	1.854	−.727	.237	.045	-	-
mar03	1.970	−.716	.245	.032	-	-

√ See the same **variation between sets** as in real data! And new **phase shifts move** the g_{E_1}value.

10. Two Checks for 4- versus "2+2"-parameter Fits

√ **Assuming** that all goes as planned and **the systematics are under control**, what exactly can be shown at DPF 2003?

√ Used some **intermediate values** for the parameters. **The results of the fit do not change** if one:

1. **fixes** g_{M_1} **and** $\frac{a_1}{a_2}$ to the DPF2002 values and then fits for g_{E_1} and $\frac{a_1}{a_2}$.
2. **assumes constant for** g_{E_1} rather than the $E_{e^+e^-}$-dependent FF.

When and What?	**Measured Values**					
	$\tilde{\mathbf{g}}_{\mathbf{M_1}}$	$\mathbf{a_1/a_2}$, GeV^2/c^2	$\lvert\mathbf{g_{CR}}\rvert$	$\frac{\lvert\mathbf{g_{E_1}}\rvert}{\lvert\mathbf{g_{M_1}}\rvert}$	$\mathcal{A}$, %	$\mathcal{BR}$, $\times 10^{-7}$
'97+'99, DPF2002	$1.10 \pm .10$	$-.75 \pm .03$	-	-	13.3 ± 1.4	-
", ", Madison	$1.20 \pm .13$	$-.73 \pm .03$	$.19 \pm .01$	-	-	-
", ", Sept 2002	$1.15 \pm .12$	$-.73 \pm .02$	$.18 \pm .02$	$< .03$	-	-
", ", Jan 18, 2003	$1.14 \pm .12$	$-.73 \pm .02$	$.20 \pm .01$	$.09 \pm .03$	14.1 ± 1.4	-
4-par	1.152	$-.732$	.223	.100	-	-
2+2-par	1.10	$-.75$	.228	.104	-	-
4-par, E1 = const	1.150	$-.730$	.224	.063	-	-
2+2, E1 = const	1.10	$-.75$	.229	.068	-	-

11. Conclusions

- √ **Complete set of results** have been obtained and studies of systematics are ongoing.
- √ **The new systematic effect** has been discovered. However, there is an indication the problem i **perhaps in the Likelihood Function**, in which case it would be under control.
- √ **Either 4- or 2-parameter fit** can be used for obtaining the actual results to be presented at DPF. The **4-parameter fit will be used for the final results**, i.e. the ones approved for publication.

$$\mathbf{g_{M1}} = \mathbf{1.27} \pm \mathbf{0.12}(\mathbf{stat}) \pm \mathbf{0.19} \pm \mathbf{0.06}(\mathbf{DPF02})$$

$$\frac{\mathbf{a_1}}{\mathbf{a_2}} = -\mathbf{0.71} \pm \mathbf{0.03}(\mathbf{stat}) \pm \mathbf{0.02} \pm \mathbf{0.02}(\mathbf{DPF02})$$

$$\mathbf{g_{CR}} = \mathbf{0.25} \pm \mathbf{0.01}(\mathbf{stat}) \pm \mathbf{0.05} \pm \ldots$$

$$\frac{|\mathbf{g_{E1}}|}{|\mathbf{g_{M1}}|} = \mathbf{0.14} \pm \mathbf{0.03}(\mathbf{stat}) \pm \mathbf{0.07} \pm \ldots$$

$$\mathcal{A} = (\mathbf{13.9} \pm \mathbf{1.4}(\mathbf{stat}) \pm \mathbf{0.04} \pm \mathbf{0.01}(\mathbf{DPF02}))\,\%$$

$$\mathcal{BR} = (\mathbf{3.67} \pm \mathbf{0.07}(\mathbf{stat}) \pm \mathbf{0.01} \pm \ldots) \times \mathbf{10^{-7}}$$